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NONLINEAR OPTICAL PHASE CONJUGATION TECHNIQUES TO REDUCE THE PHYSICAL SIZE OF LASERS

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Optical phase conjugation involves the use of various techniques to reverse the wavefront of an optical beam. Nonlinear optical interactions within various media may be used to generate phase conjugation. This report reviews the most promising techniques for nonlinear optical phase conjugation and postulates how phase conjugation might be used to reduce the physical size of laser systems. A number of examples from literature are cited.

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I. INTRODUCTION

Optical phase conjugation (OPC) involves the use of various techniques to reverse the wavefront of an optical beam. Expressed mathematically as an electromagnetic wave, an optical beam has a complex exponential notation with a directional propagation factor, phase factor, time factor, and amplitude. Merely reversing the direction of propagation with an ordinary mirror does not reverse or correct the aberrant characteristics given by the phase factor. However, if the conjugate of the phase factor could also be realized, then an optical beam would result that exactly retraced its path. A divergent beam would converge, and vice versa. Aberrations introduced by passing through a distorting media would be "undone" as the phase conjugate beam passes back through the same distorting media.

Many techniques have been used to generate optical phase conjugation or an approximation thereof. Coherent optical adaptive techniques (COAT) have involved the use of mechanically deformable or segmented mirrors, electronic feedback, and servo-controls to correct for distortions introduced by an optical system or the atmosphere. The term pseudoconjugation has been applied to the use of corner mirrors, arrays, and similar optics [1][2]. An optical resonator, such as a stable laser mirror configuration, can also be thought of as a form of pseudoconjugator.

This report addresses only one class of optical phase conjugation, that which involves the use of nonlinear optical interactions within various media. Nonlinear optical phase conjugation (NOPC) has been demonstrated in solids, liquids, and gasses with optical sources (particularly lasers) at many wavelengths and by number of different mechanisms. The most important and promising techniques are reviewed in this study.

The purpose of this report is to address how NOPC techniques might be used to reduce the physical size of laser systems. The approach would particularly involve a reduction in the size of the laser's optical system, which may have been undesirably large to correct for beam divergence, beam wander, pointing errors, and other flaws. In addition, the use of NOPC techniques might also allow the use of optical components which would otherwise be rejected in compact laser designs. NOPC is a relatively new field, and much is still to be learned about the advantages it may introduce.

A. Description of Optical Phase Conjugation

If an optical beam is made to precisely reverse both the direction of propagation and the phase factor for each component of the beam, then the beam is said to be phase-conjugated. The beam would behave exactly as it would have if time had been reversed, and so the terms "wavefront reversal" and "time reversal" are often used.

Following the discussion in Reference 3, an optical beam may be expressed in complex exponential notation as:

$$E(x,y,z,t) = A(x,y)e^{i[kz+\phi(x,y)-wt]} + c.c. \qquad (1)$$

where c.c. is the complex conjugate. In this equation, z is the direction of propagation, the wavelength is $2\pi k$, and the beam amplitude is given by A(x,y). The phase factor $\phi(x,y)$ indicates how the optical wave deviates from a uniform plane wave in the form of divergence, aberrations, distortions, etc.

If this wave is incident upon an ordinary flat mirror, the direction of propagation will be reversed at an angle depending upon the tilt of the mirror as shown in Figure 1(a). The phase factor (depicted, for example, as a diverging beam in the figure) will still exist and is unmodified by the flat mirror. However, if a perfect phase conjugate mirror (PCM) were used instead, the reflected beam would be exactly reversed in direction and phase, regardless of the tilt of the mirror. For the example in Figure 1(b) the beam would converge back to its source. This phase conjugate beam would now have the mathematical expression:

$$E(x,y,z,t) = A(x,y)e^{i[-kz-\phi(x,y)-wt]} + c.c. \qquad (2)$$

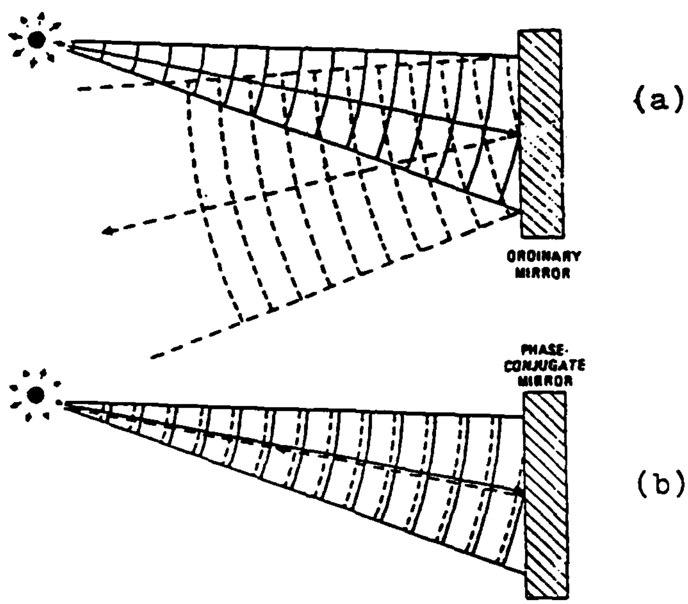

Figure 1. (a) Comparison of an ordinary mirror and (b) a phase conjugate mirror.[4]

Here the signs of the spatially dependent terms have both been reversed in the exponent. Note also that if only the time, t, had been reversed in Equation (1) the resulting expression would be of the same form. So the phase reversal is mathematically equivalent to a time reversal.

If the beam reflected from a PCM retraces its path through a distorting medium, the effects of the distortion will be neutralized. This is to be expected from the principle of optical reciprocity or reversibility. Consider, for example, the introduction of an optical wedge in front of an ordinary mirror and a phase conjugate mirror as shown in Figure 2. In all cases the incident beam will be deviated by the wedge. If the refracted ray then strikes the ordinary mirror and is reflected back to the wedge, it will emerge at a new angle as in Figure 2a. The beam will not retrace its path except for the singular case of the mirror being normal to the incident ray (Fig. 2b). However, for the phase conjugate mirror shown in Figure 2c the beam will always retract its path, even if the wedge is removed or a different wedge angle is inserted.

Note that for a few simple cases (Fig. 1 and 2), a conjugate wave can be created with ordinary mirrors under certain restricted conditions. If the optical beam is a plane wave in Figure 2b, the plane mirror can be precisely tilted to conjugate the incident wave. If the wedge is tilted, removed, or replaced by a different wedge angle, the plane mirror must be realigned. Similarly, for a spherical wave front as in Figure 1a, the plane mirror could be replaced by a concave spherical mirror that exactly matches the wave front. The spherical wave would then be reflected precisely back to its source.

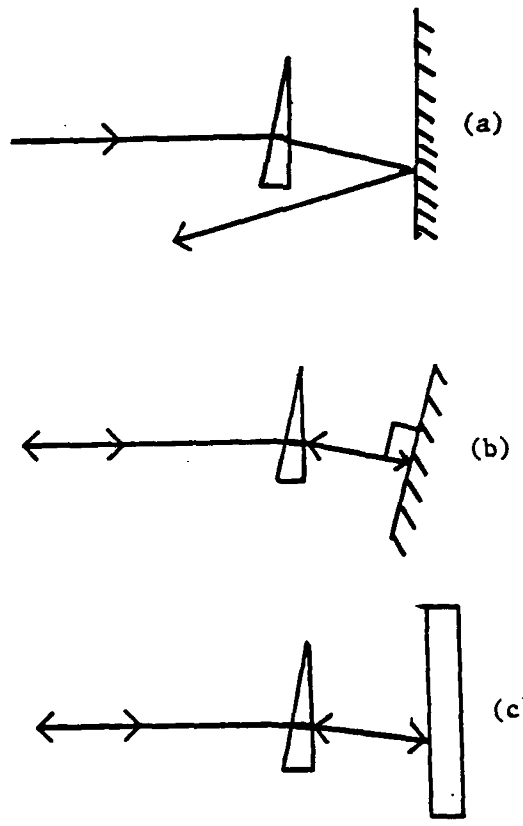

Figure 2. Effects of an optical wedge on an incident ray for an (a) ordinary mirror, (b) ordinary mirror positioned normal to ray, and (c) phase conjugate mirror. [5]

For any random, imperfect, and complicated wave front, the task is infinitely harder. Only under special conditions can ordinary mirrors be utilized to conjugate a beam. Some of these techniques are possible in nearly plane or spherical wave fronts as might be encountered in lasers, which have the additional advantage of monochromaticity. One could imagine the design of a very special mirror to conjugate a predetermined wave front. Deformable mirrors and other adaptive optical techniques have also been used, but the wave front must be precisely characterized or predicted for such measures to be effective. Should the shape of the wave front then change, the shape of the mirror also has to change to match the beam.

Fortunately the use of nonlinear effects to produce phase conjugation has none of these disadvantages. With NOPC techniques the optical beam can have an arbitrary, heavily distorted wave front that can even be varying with time. A few restrictions will still exist, however. NOPC generally requires a monochromatic light source and changes to the distorting medium must be slower in time than the round-trip propagation of the wave front through the distortion.

B. Applications

Before reviewing the nonlinear processes by which optical phase conjugation can be produced, some generalized applications will be considered. The first application involves the use of OPC in a laser resonator. If one or both of the cavity mirrors are replaced by a PCM, a phase conjugate resonator (PCR) may be formed [6]. The PCR can automatically compensate for aberrations within the optical elements, static misalignment, thermal distortions and dynamic misalignment, mechanically induced perturbations, etc. Resonator stability is not a problem, as has been demonstrated by using an ordinary metal kitchen spatula as one cavity mirror! Figure 3 shows a typical configuration of a PCR.

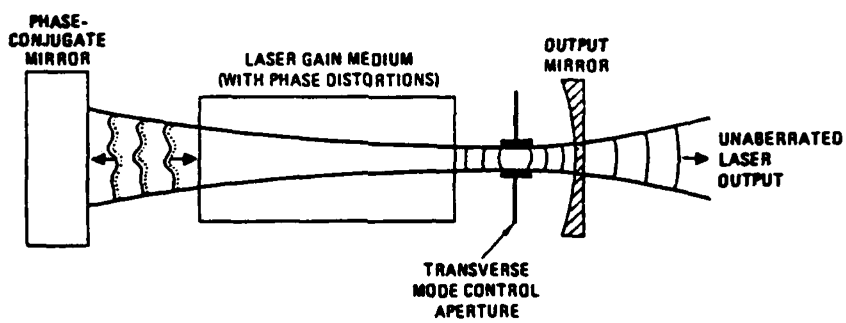

Figure 3. Simplified diagram of a phase conjugate resonator [4].

As a second application, NOPC techniques can be used to compensate for distortions in high-power laser amplifier systems. O'Meara has assessed a number of optical schemes for doing so [7]. The simplest approach is to use a low-power oscillator which is relatively free of thermal distortions and other aberrations, and then couple the output into a high-power amplifier with a phase conjugate mirror. If, for example, the amplifier is in a double-pass arrangement (Fig. 4), the distortions introduced in the first pass through the amplifier will be compensated in the second pass.

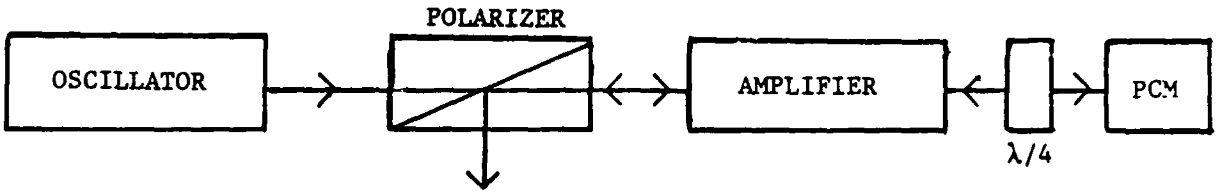

Figure 4. Optical phase conjugation in a laser amplifier [3].

Self-targeting of radiation [8] is a third application which might be used in thermonuclear fusion or even some weapon applications. Figure 5 illustrates this principle. A low-power laser is directed to the target (such as a fusion pellet) without the need for a complicated set of mirrors or lenses. Of all the light reflected from the target, some of the light would be directed into a high-power phase conjugating amplifier. The amplifier would be used to intensify the low-power probe beam and redirect the beam back to the target, producing the desired heating effect on the target.

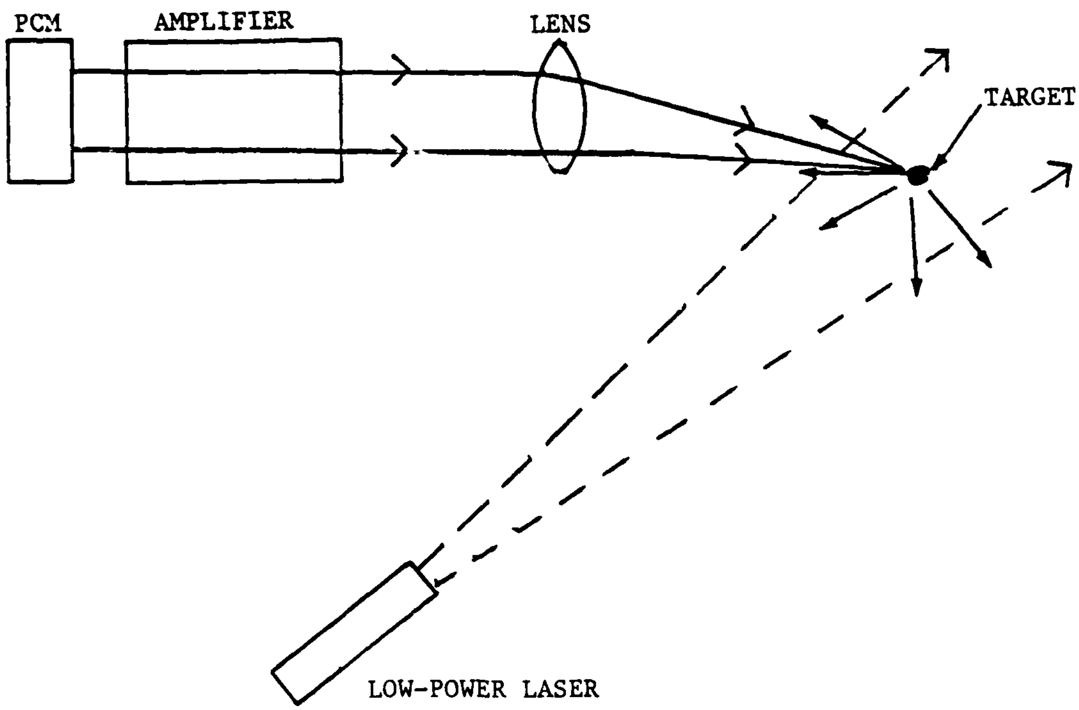

Figure 5. Self-targeting of laser radiation with a phase conjugate amplifier [8].

Optical phase conjugation might be used to correct for distortions in fiber optic cable transmissions [6]. In this application the distortions introduced in one cable might be corrected by a phase conjugate wave traversing a second identical cable.

O'Meara [9] has addressed the use of NOPC techniques to compensate for atmospheric turbulence-induced degradations in active imaging systems. The two-way atmospheric path must, of course, have time-varying distortion elements which vary slowly compared to the round-trip propagation time of the laser pulse. (For a range of 10 km the round-trip propagation time at the speed of light is less than 70 μs.)

Other potential applications include the use of NOPC for commercial photolithography in the microelectronics manufacturing process [6], optical memory and pattern recognition [6], laser pulse compression [10], and laser spectroscopy.

C. Historical Notes

References 4, 5, and 8 each give insights to the many early developments which have contributed to the field of optical phase conjugation. In 1965 Kogelnik observed that conventional holographic techniques could be used for imaging through static inhomogeneous media. In retrospect, much of the early work in dynamic or transient holography is related to NOPC, but was not treated as such at that time. The discovery of stimulated Raman scattering in 1962 at the Hughes Aicraft Company and stimulated Brillouin scattering in 1964 at the Massachusetts Institute of Technology gave nonlinear processes which could eventually be applied to phase conjugation.

Zel'dovich and his fellow workers at the Lebedev Physical Institute in Moscow were probably the first to observe a direct consequence of NOPC in 1972. At that time the red beam from a pulsed ruby laser was intentionally distorted by a nonuniform glass plate that had been etched with hydrochloric acid. The distorted beam was then directed into a 1 m length of pipe filled with gaseous methane at 14 atmospheres pressure. Stimulated Brillouin scattering occurred in the pipe, and the beam was reflected back through the glass plate, from which it emerged nearly undistorted. This discovery led to additional work in the Soviet Union, the United Sates, and other countries, and today stimulated Brillouin scattering is one of the two most promising techniques for creating NOPC.

In the mid to late 1970's additional advances were made in the mixing of two, three, and more optical waves in a nonlinear medium to generate a conjugate wave. Four-wave mixing of optical beams is now also a popular method for NOPC. Many other nonlinear effects hve been used to generate the conjugate of optical waves, and several of these will be reviewed in the following section.

II. TECHNIQUES FOR GENERATING PHASE CONJUGATION

In this chapter several classes of nonlinear optical interactions that can yield conjugate wave fronts will be presented. In Reference 4 Pepper has categorized each of these processes into two groups: (1) optical parametric interactions which produce elastic photon scattering and (2) stimulated photon interactions which lead to inelastic scattering. The first group, elastic photon scattering, means that the nonlinear medium which produces NOPC is left in the same quantum state as before the interaction. The medium neither gains nor loses energy, so by conservation of energy the resulting conjugate wave must necessarily be a sum or difference frequency of the waves in the mixing process.

In contrast, the inelastic photon scattering processes all involve a transfer of their energy to the nonlinear medium. Examples include stimulated Brillouin, Raman, and Rayleigh scattering. The energy transferred to the medium can be in the form of acoustic phonons (pressure-density fluctuations) or molecular vibrations. Due to this energy transfer to the nonlinear medium, the conjugate wave is of lower energy (longer wavelength) than the incident wave.

Each of the two categories of conjugation techniques have their advantages and disadvantages. The elastic interactions can produce (in some instances) a conjugate of the same wavelength as the initial beam. A critical threshold intensity for operation is not required and the interaction is not lossy. However, more than one beam is necessary for the interaction to occur.

In contrast, the inelastic scattering processes are passive in nature, not requiring any beam other than that to be conjugated. The disadvantages are that the interaction is lossy, the conjugate wave is frequency shifted from the original, and a threshold intensity must be exceeded for the interaction to occur.

Several of the more important nonlinear processes are reviewed in the following.

A. Three-Wave Mixing

The process of three-wave mixing (TWM) involves two intense monochromatic waves incident upon a nonlinear material such as a crystal lacking inversion symmetry. This process was first proposed by Yariv in 1976 [11]. In TWM an incident probe wave and a pump wave of a different frequency interact in the crystal to produce a forward-going conjugate wave at the difference frequency.

Avizonis, et al. [12] has demonstrated three-wave mixing with a Nd:YAG laser at its fundamental wavelength of 1.06 μm and its frequency doubled (green) wavelength of 0.53 μm serving as the probe and pump beams, respectively. Both beams interact in a lithium formate crystal to produce a conjugate wave at 1.06 μm. This resulting wave is free from distortions that were deliberately imposed on the original probe beam.

Three-wave mixing techniques have not proven very useful because of severe phase-matching constraints that are necessary for forward-going conjugate waves. As a result TWM is not being seriously pursued. Instead, certain forms of four-wave mixing are much more promising.

B. Four-Wave Mixing

In the phase conjugation process of four-wave mixing (FWM), three input waves interact in a nonlinear medium to produce a fourth complex conjugate of one of the input fields. The fourth wave can be either forward-going or backward-going, depending on the geometry of the setup. The backward-going interactions do not require strict phase matching and offer more potential for practical applications [4].

One of the input waves is designated the probe wave and the other two are the pump waves. The conjugate wave has a frequency $fc = f1 + f2 - f3$ where f1 and f2 are the pump frequencies and f3 is the frequency of the probe wave. For the special case that the three input beams are all the same wavelength, the conjugate wave will also be at this wavelength. This process is known as degenerate four-wave mixing (DFWM) and should prove most useful for many potential applications.

The two pump waves are chosen to propagate in opposite directions to each other, and likewise the conjugate wave will be exactly reversed in direction of propagation from the probe wave, regardless of the angle of the input probe wave. The special case of degenerate four-wave mixing therefore comes closest to the ideal PCM previously described in Figures 1 and 2. This configuration can also lead to gain whereby the conjugate wave has an amplitude greater than the probe wave. Such resonantly enhanced DFWM has been reviewed by Lind et al. [13].

Degenerate FWM has been demonstrated at many ultraviolet, visible, and infrared laser wavelengths in nonlinear gases, crystals, semiconductors, and dyes [4]. Often the term "Kerr-like media" is used to denote nonlinear materials in which the speed of light (or index of refraction) varies with the optical intensity. Suydam and Fisher [14] have reviewed the transient effects of mixing in Kerr-like materials.

C. Photon Echoes

Another technique for generating an elastic NOPC interaction is known as the photon echo. If a nonlinear medium is illuminated by two optical pulses slightly separated in time, a third pulse (the photon echo) may be emitted at an identical time interval after the second pulse [15]. The echo is due to atomic or molecular dipole moments that rephase in time and space after the initial interaction. Three-pulse interactions can also lead to photon echoes.

Both forward and backward propagating conjugate output echoes can be generated. Photon echoes are primarily of interest in the study of relaxation processes, atomic lifetimes, scattering cross sections, etc.

Other elastic nonlinear optical interactions have been investigated for phase conjugation [4]. These include saturable absorbing media, plasmas, nonlocal field effects such as photorefraction and electrostrictive effects, thermal effects, and surface effects.

D. Stimulated Brillouin Scattering

The first inelastic photon scattering interaction to be reviewed is the stimulated Brillouin process, or SBS, whereby acoustic phonons (pressure-density fluctuations) are created in the nonlinear medium. As a result of this inelastic process a backward-going, frequency downshifted phase conjugate wave is generated. In Soviet literature SBS in known as stimulated Mandelshtam-Brillouin scattering, or SMBS [16].

Stimulated Brillouin scattering has received a great deal of attention because of its simplicity in operation and its high effeciency [17]. Although a threshold is required for operation, it can easily be met because SBS exhibits a large cross section for interaction. No other pump wave is required, so the optical system can be quite simple.

The conjugate wave is frequency downshifted as a Stokes wave, typically on the order of 1 cm^{-1} [10]. This small shift may be inconsequential for many applications. For example, at a nominal laser wavelength of 1.064 μm, a 1 cm^{-1} shift in frequency corresponds to an increase in wavelength of slightly more than 1 angstrom. Most system applications do not require such tight frequency stability.

The efficiency of the SBS process has been measured as high as 90 percent, but in system applications, values of 30 to 50 percent are typically chosen to preclude the possibility of optical damage [17]. The SBS process leads to pulse compression which can increase the likelihood of optical damage due to high flux levels.

Hon [10] first demonstrated that laser pulses could be significantly compressed by SBS. By confining the nonlinear medium in a tapered waveguide, the threshold intensity for SBS interaction could be obtained in the Brillouin cell. The backward-going conjugate wave is compressed in pulsewidth. Hon was able to compress a 20 ns Nd:YAG laser pulse down to 2 ns. He used a tapered glass tube with methane at 130 atm as the nonlinear medium. The methane acted as a phase conjugate mirror. Pulse compression may prove to be a very important process for applications where high peak flux levels are needed. Controlled thermonuclear fusion is one of several applications [16].

E. Stimulated Raman Scattering

In 1962 researchers at Hughes Aircraft Company found that a strong monochromatic light source, such as from a ruby laser, could create a longer wavelength beam if the incident wave interacts with a nonlinear medium. If the medium is excited by the incident wave in the form of molecular vibrations, a process known as stimulated Raman scattering (SRS) occurs [18].

Stimulated Raman scattering has proven quite popular for the efficient generation of new laser lines. However, it has not been extensively used for purposes of phase conjugation. In some instances SRS may compete with desired SBS interactions, and SRS can also be used for extremely short pulse compression. The lack of interest in SRS is partly due to the large frequency shift, typically 1000 cm^{-1}, which occurs between the input wave and the conjugate Stokes wave [10]. This frequency shift cannot be tolerated for many applications, such as those which require narrow bandwidth receivers.

There are other inelastic photon scattering effects which might be used for phase conjugation. These include stimulated Rayleigh scattering, Rayleigh wing scattering, thermal Rayleigh scattering, stimulated polariton scattering, and others [19]. To date, however, none of these have proven important.

III. APPLICATIONS FOR SIZE REDUCTION IN LASER SYSTEMS

In this section some potential applications shall be addressed for nonlinear optical phase conjugation in laser systems. Emphasis shall be placed on techniques which might lead to smaller size and lighter weight for the total laser system.

One application might be a reduction in the size of the laser collimating optics for a conjugate beam which has lower divergence than the conventional laser beam it would replace. As an example, some Nd:YAG laser systems require a collimated beam which has a divergence on the order of 0.12 mrad at output energies of 100 to 150 mJ. In order to obtain a reasonably acceptable laser efficiency, the designer might settle for a multi-mode output beam in a 10 cm aperture. This large aperture would then dictate the volume of the collimating optics, as well as the size of any pointing mirrors, windows, and other optical elements which may be placed in the collimated beam.

Now assume that the 10 cm aperture could be replaced by a much smaller one. If a diffraction limited beam could be obtained, the size of the aperture could be reduced to approximately $2.44\ \lambda/0.12$ mrad = 2.2 cm. This would be a reduction in aperture size by a factor of 4.5, that could easily translate to a reduction in the volume of the collimating telescope by factors of 30 or more.

It is not easy to obtain a diffraction limited beam at these energy levels and with efficiencies of 1 percent or more, particularly at any useful repetition rate. Thermally induced distortions in the laser rod and other optical distortions inherent to the laser material prevent diffraction limited performance.

However, it is possible to construct a low power laser oscillator that produces a near diffraction limited beam if efficiency is not required. Then a two-pass laser amplifier can be added to the oscillator to reach the desired energy level, as previously described in Figure 4. Thermal distortions from laser rod heating and nonuniform cooling produced in the first pass through the amplifier rod would be compensated in the conjugate beam that is reflected from the phase conjugate mirror.

Hon [20] has demonstrated a similar system using stimulated Brillouin scattering in high-pressure CS_2 and CH_4. A low energy Nd:YAG laser of several millijoules was amplified to 200 mJ. The beam was then further distorted by passing it through another highly pumped rod. A total of 730 mJ of diffraction-limited output at 10 Hz was extracted.

In a more recent experiment, Rockwell and Giuliano [21] used a low energy Nd:YAG laser to pump several parallel amplifiers, each of which employed a single SBS mirror of high pressure methane. A single coherent output beam was obtained, despite large differences in optical path lengths and amplifier energies.

Another approach to obtaining a diffraction limited output beam would be to use a phase conjugate resonator configuration (Fig. 3). Belanger et al. [22] and Siegman et al. [23] have addressed this approach as have other researchers. AuYeung et al. [24] were the first to demonstrate a phase conjugate resonator, using degenerate four-wave mixing in CS_2 from a ruby laser. Phase conjugate resonators have also been constructed with SBS and other techniques. (Many of these resonator designs are extremely complex, compared to the simple design outlined in Figure 3!)

The complex designs of some phase conjugate resonators led Chandra et al. [25] to propose placing the phase conjugate mirror in a sidearm which was polarization coupled to a conventional resonator. The sidearm produced a Q-switched output as threshold was reached. The laser output varied considerably and showed periodic pulse substructures which were related to optical path lengths in the laser.

Another approach to reducing the size of a laser system might involve replacing one type of laser with a more efficient material. NOPC techniques could assist in making this change feasible. As an example, the solid-state laser material Nd,Cr:GSGG promises to be two to three times as efficient as Nd:YAG and with an output line at almost the same position in the spectrum. The newer material might allow a much smaller power source (e.g. batteries), a smaller power supply, and a smaller cooling system.

Unfortunately the broad pump bands in Nd,Cr:GSGG result in thermal distortions and birefringence that are much worse than in Nd:YAG. Perhaps NOPC techniques could be used to remove this distortion and allow use of the more efficient GSGG material.

Reducing the length of the resonator might be another approach to obtaining a smaller laser system. Many resonators are purposely long to obtain good mode structure and low beam divergence. However, a shorter resonator might be acceptable if NOPC techniques were used to maintain good beam quality.

Although many of the experimental phase conjugate mirrors are quite long, compact designs are possible. Hon [17] has proposed an SBS cell which is a glass fiber made into a coil. Phase conjugate mirrors using the photorefractive effect have been demonstrated in small crystals such as barium titanate [26] and strontium barium niobate [27].

The combination of more than one NOPC technique may also be used. Skeldon et al. [28] have used an SBS phase conjugate mirror to produce the backward-going pump wave for a four-wave mixing process. Kwong et al. [29] have demonstrated the use of a multimode optical fiber in tandem with a $BaTiO_3$ crystal as a photorefractive phase conjugate mirror. The fiber is used to undo nonreciprocal polarization effects by scrambling the polarization.

A phase conjugate laser system might also replace a larger laser if the application requires high peak flux levels. Consider, for example, laser applications such as rangefinding and thermonuclear fusion. If very short pulses are obtained, peak powers may be higher for a conjugate laser whose average energy and size are smaller than for a conventional laser. Techniques such as pulse compression by stimulated Brillouin scattering [10] could be used. Thus, a smaller laser (but with higher peak power) might fit the application.

Research continues in NOPC processes at a number of locations, with frequent announcements of new discoveries in the scientific literature.

IV. CONCLUSIONS

Nonlinear phase conjugation techniques promise a number of improvements in laser systems which may result in higher energy and improved beam quality; freedom from static and dynamic misalignments; freedom from thermal, acoustical, and mechanical perturbations; correction for atmospheric distortion; and possibly more compact laser systems.

For correction of distortions in medium and high power laser systems, phase conjugate amplifiers appear quite attractive. Hon [17] has summarized the following important system implications for a high power master oscillator/power amplifier (MOPA) configuration that uses SBS phase conjugation in a Nd:YAG laser:

a. The SBS cell serves as a passive optical isolator until threshold is reached, resulting in higher efficiency, greater output pulse energy, and better beam quality.

b. Polarization must be carefully controlled. Along with thermal distortion, thermally-induced birefringence occurs in the amplifier rods.

c. Output levels at good efficiencies can be obtained over a wide range by a choice of small or large laser rods.

d. The single-mode master oscillator need only have an output of 1 to 5 mJ, and could be operated up to several hundred Hz without producing excess distortion.

e. The same process could be used with other lasers, assuming several criteria are met. An efficient SBS mirror must exist, and the Stokes shifted linewidth must still fall within the gain linewidth of the amplifier.

Phase conjugate resonators are also attractive for many applications. However, since resonator configurations are generally much more complex than laser amplifiers, there are many more design challenges to a PCR.

Much work is still needed to understand fully all the implications of nonlinear phase conjugation in laser systems. Damage thresholds of exotic nonlinear materials must be investigated. High pressure seals and lifetimes of gases and liquids must be proven. Optical properties such as polarization and induced birefringence (which may not be conjugated) must be appropriately controlled. Performance of the laser systems at environmental extremes will have to be demonstrated. Finally, the rather large experimental devices now being investigated must be packaged in compact, efficient designs.

Researchers in this fascinating field consider it to be only a short time until NOPC techniques are employed in a number of practical applications.

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